Wind Farm Group Efficiency - A Sensitivity Analysis with a Mesoscale Model

Volker, Patrick; Badger, Jake; Hahmann, Andrea N.

Publication date:
2014

Citation (APA):
Volker, P., Badger, J., & Hahmann, A. N. (2014). Wind Farm Group Efficiency - A Sensitivity Analysis with a Mesoscale Model. Poster session presented at European Wind Energy Conference & Exhibition 2014, Barcelona, Spain.

PO.ID 128

Wind Fram Group Efficiency - A Sensitivity Analysis with a Mesoscale Model

Patrick J.H. Volker, Jake Badger, Andrea N. Hahmann

DTU Wind Energy, Roskilde, Denmark

DTU

DTU Wind Energy
Department of Wind Energy

Abstract

In the North Sea the total installed capacity was in 2012 5 GW, and it estimated that it will grow to 40 GW by 2020 (EWEA). This will lead to an increasing wind farm density in regions with the most favourable conditions. In this study, we investigate the sensitivity of power density losses to wind farms that are in the wake of an upstream wind farm.

Introduction

The estimation of the power losses caused by upstream wind farms is challenging, since a whole range of spacial scales is involved. On the largest (meso) scales, the advection of the wind farm wakes effects the production at downstream wind farms, whereas on smaller (micro) scales single turbine wakes determine the local wind farm production. In the past year, studies with Large Eddy Simulations of entire wind farms have been published. Furthermore, the large European Energy Research Alliance - Design Tool for Offshore Wind Farm Cluster (EERA-DTOC) project started recently with the aim to develop design tools for wind farm optimisation. Here we investigate with a mesoscale model, the sensitivity of wind farm shadowing from up-stream wind farms for 3 different climates, 2 wind farm sizes and 2 wind farm spacing.

Wind Farm Parametrisation

The Explicit Wake Parametrisation (EWP) (?) considers the unresolved wake expansion in the turbine containing grid-cells, where the velocity gradients are the largest. The wake expansion is described by the diffusion equation. The assumptions are that the diffusions coefficient, K, is constant in the wake and that the advection velocity, U_0, is at hub-height, h.

The velocity profile in the turbine wake is:

$$\underbrace{U_W(x,z)}_{\text{Wake velocity}} = \underbrace{U(x,z)}_{\text{Unresolved velocity}} - \underbrace{U_s(x)\, f(z)}_{\text{Velocity deficit}}$$

where z is the vertical direction. The velocity deficit can be described as a maximum velocity defcit at the wake's centre U_s times the function $f = \exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma}\right)^2\right]$, where σ is the measure of the vertical wake extension. The measure of vertical wake extension σ and U_s are:

$$\sigma^2(x) = \frac{2K}{U_0}x + \sigma_0^2 \qquad \begin{cases} \sigma_0 & \text{initial length scale} \\ U_0 & \text{hub}-\text{height velocity} \end{cases}$$

$$U_s(x) = \sqrt{\frac{\pi}{2}}\,\frac{C_T\, R_0^2\, U_0}{2\,\Delta y\, \sigma}. \qquad \begin{cases} C_t & \text{thrust coefficient} \\ R_0 & \text{turbine rotor radius} \\ \Delta\, y & \text{horizontal grid}-\text{spacing} \\ z_{max} & \text{height of the domain} \end{cases}$$

In the mesoscale model we apply Gaussian velocity deficit, with a grid-cell averaged vertical wake extension to the model velocity equations,

$\overline{\sigma} = \frac{1}{L}\int_0^L \sigma\, dx$, where L is the horizontal wake extension.

Model Configuration

For this study the Weather Research and Forecast (WRF) model (?) in the "idealized case" mode is used. The most important model settings are listed in the table below:

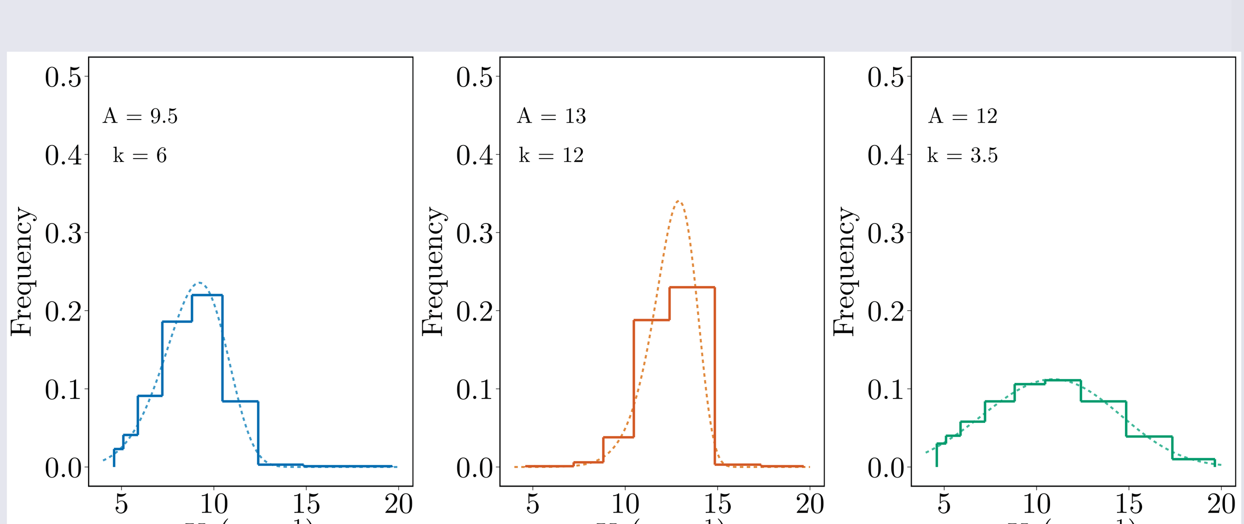
Wind direction (°):	270
Geostrophic Wind speed ($\mathrm{m\,s^{-1}}$):	4 / 5 / 6 / 8 / 9 / 11 / 13 / 16 / 18
Horizontal grid spacing (m):	1120
Number of grid-cells (nx,ny,nz):	150, 40, 40
Horizontal domain size x, y (km, km):	168, 44.8
Boundary condition:	OPEN
Pert Coriolis:	Yes
PBL scheme:	?

Every simulation was run with and without wind farm. The first one has been used to obtain the power production without the wake effects of individual turbines. The simulations with the individual wind speeds have been used for the computation of the different wind climates.

Wind Climate

The wind farm power production density is analysed for the reference simulation (without wind farm), for the upstream wind farm and for the downstream wind farm for three different wind climates.

In the figure to the left the Weibull distributions and histograms of the individual simulated wind speed bins for the three different wind climates are shown. The wind climates are obtained by the weighting of the individual wind speeds and are denoted by C1, C2 and C3 from left to right.



References

Nakanishi, M., and Niino, H.. Development of an improved turbulence closure model for the atmospheric boundary layer. *J of the meteorol Soc of Jpn*, 87:895-912, 2009.

Skamarock, W., Klemp J., Dudhia J., Gill, D., Barker, D., Duda M., Huang X., Wang W., and Powers, J,. A Description of the Advanced Research WRF Version 3. *NCAR Technical note*, 2008.

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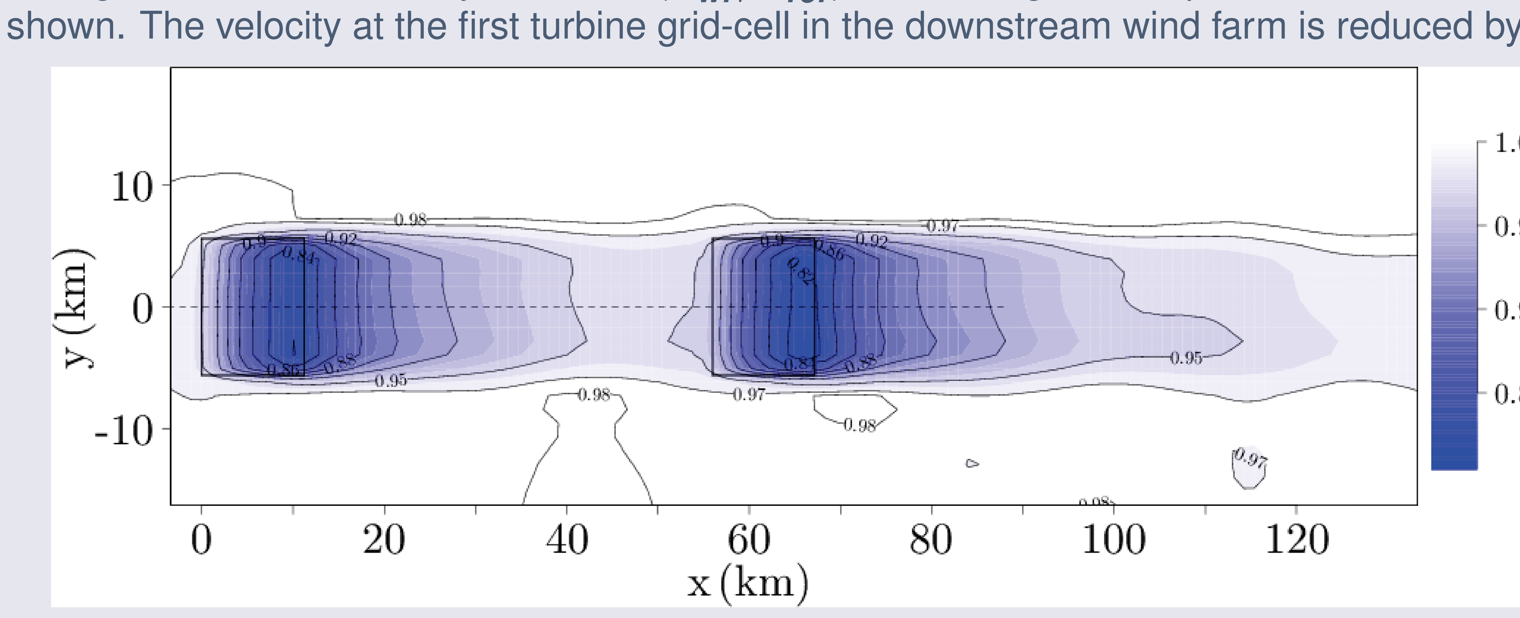
Experimental Set-Up

All wind farms are composed of Vestas V80 (2MW) turbines. The wind farms contain 100 (small) and 400 (large) turbines and extend 5 and 10 grid-cells. The wind farm seperation is 2 (near) and 3 (far) wind farms. The wind farm separation is 11.2 km, 15.8 km, 22.4 km and 33.6 km for the four experiments. The wind farm setup depicted in the figure to the left.

Exp.1) $n = 5$ (small) and $m = 2$ (near)
Exp.2) $n = 5$ (small) and $m = 3$ (far)
Exp.3) $n = 10$ (large) and $m = 2$ (near)
Exp.4) $n = 10$ (large) and $m = 3$ (far)

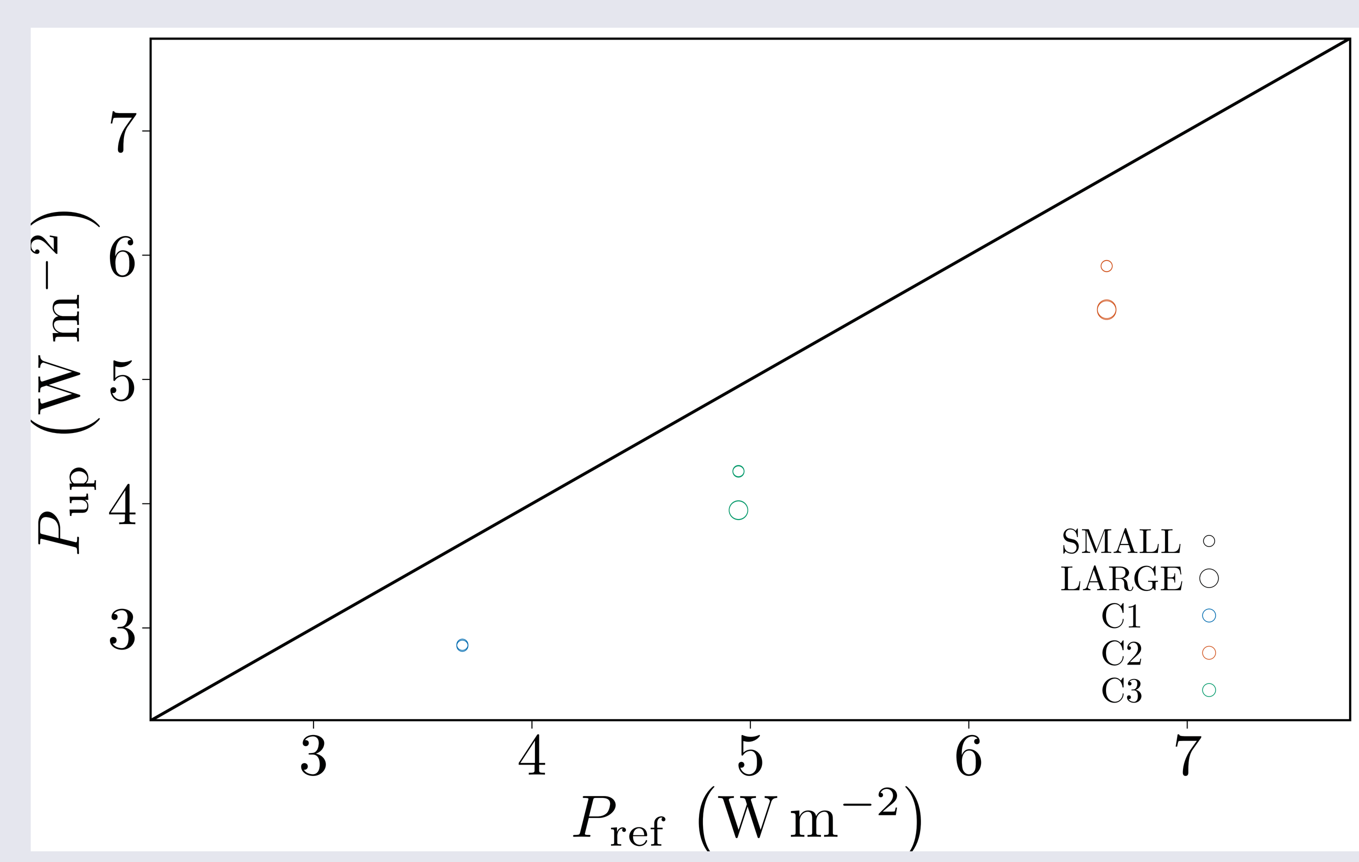
Results

In the figure below the velocity reduction (U_{wf}/U_{ref}) at hub-height for Experiment 4 and C3 climate is shown. The velocity at the first turbine grid-cell in the downstream wind farm is reduced by 5%.



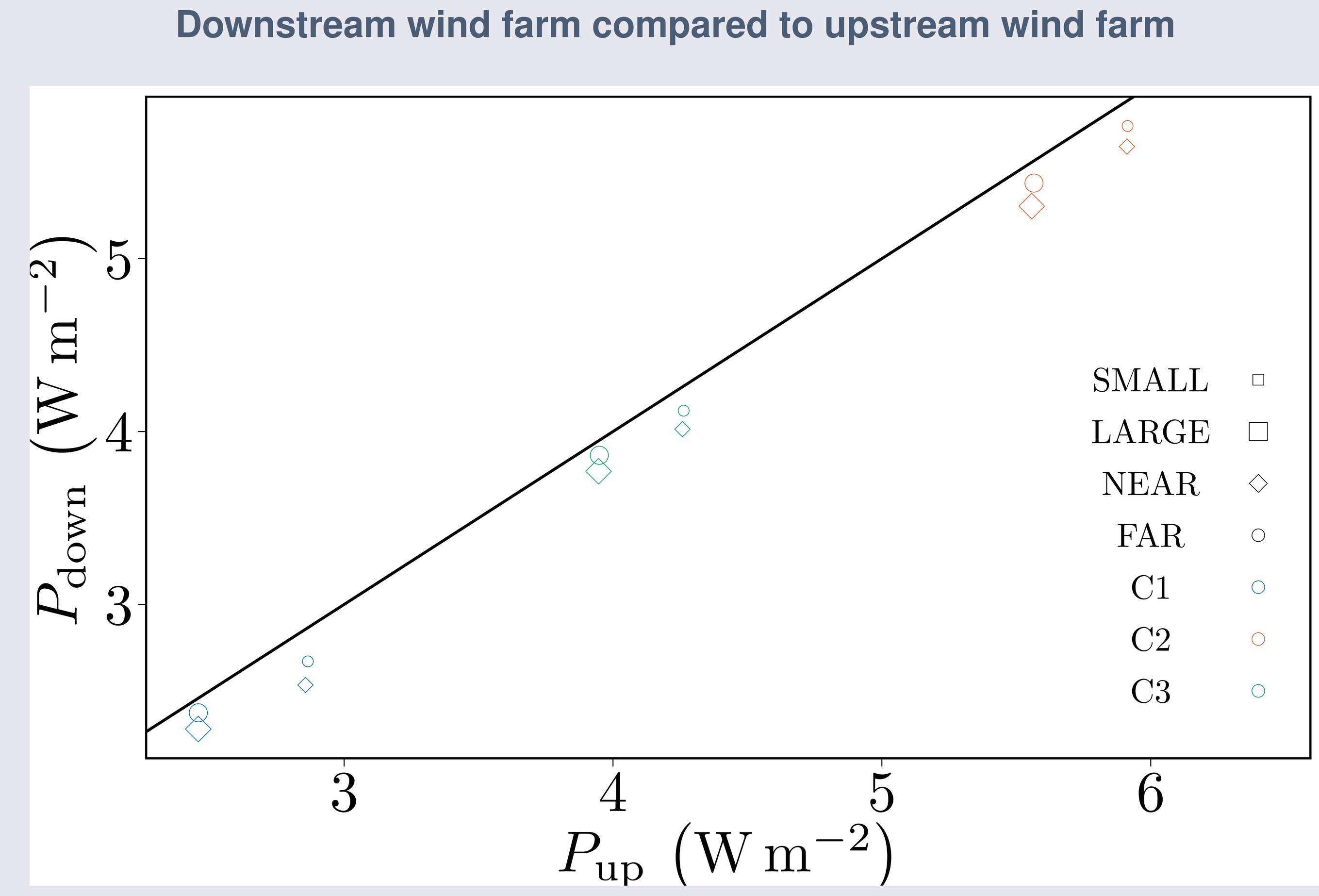
For all 4 experiments with 3 different climates, the power density of the reference simulation (P_{ref}) (without turbine-induced wakes), the upstream (P_{up}) and downstream (P_{down}) wind farm is determined.

Upstream wind farm compared to reference simulation



The power density reduction decreases for higher power densities. The power density reduction, $(P_{ref} - P_{up})/P_{ref}$, is 22.4%, 10.8% and 8% for the C1, C3 and C2 wind climate, respectively.

Downstream wind farm compared to upstream wind farm



The power density reduction ranges from 11.3% for the small wind farms with a 2 wind farm spacing for the C1 wind climate, up-to 2.2% for the small wind farms with a 3 wind farm spacing for the C2 wind climate. The ratio between the power density reduction of the small and large wind farm with a 2 and 3 wind farm spacings is around 0.5.

Conclusions

The power reduction varied from 2.2% up-to 11.3%. The power density reduction reduced almost universally for all wind climates and wind farm sizes by 50%, when the spacing increased from 2 to 3 wind farm sizes.

Funding

This study was supported by the European Energy Research Alliance - Design Tool for Offshore Wind Farm Cluster (EERA-DTOC)